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SOME BASIC PARAMETERS ASSOCIATED WITH THE FLOOD RAINS AT CHICAGO, OCTOBER 9-12, 1954

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ABSTRACT

The development of heavy rains during the period October 9-12, 1954, which led to record floods in the Chicago area, is investigated. An attempt is made to ascertain whether the low-level convergence and vertical motion could be accounted for by terms in the vorticity equation associated with vorticity advection, thermal advection, and stability. Moisture transport into the area is also analyzed.

1. INTRODUCTION

The present investigation was begun as part of a program for studying convergence in the lower troposphere and associated precipitation patterns. The program has been conducted jointly by the Weather Forecasting Research Center at the University of Chicago and the U. S. Weather Bureau Forecast Center in Chicago.

The period of heavy rainfall during October 9-12, 1954 is significant not only because of the record floods in the Chicago area, and the great amount of property damage [1], but also because the largest (for that area) recorded 48-hour accumulations of rainfall occurred. From the synoptic meteorologists' point of view the situation was especially interesting because the thundershowers occurred mostly in the warm air south of a front which was in the general vicinity during this period, and the mechanism for releasing the instability was not immediately clear.

The excessive amounts of rainfall appeared to be confined almost entirely to extreme northern Illinois as depicted in an isohyetal map (fig. 1) of official Weather Bureau reports and unofficial reports collected by the Illinois State Water Survey [2].

For a more complete synoptic description of this series of showers the reader is referred to the paper by Nash and Chamberlain [3]. Two sea-level charts from their study are reproduced in figures 2 and 3 for synoptic orientation.

The purpose of this paper is to examine quantitatively several basic factors related to the rainfall occurrence. An attempt is made to explore in some detail the occurrence of low-level convergence as implied by some of the parameters suggested by Petterssen's [4] development equation and to describe certain features of the low-level moisture jet.

2. APPLICABILITY OF TERMS IN THE DEVELOPMENT EQUATION

The development equation (Petterssen [4]) defines development in terms of low-level convergence or vertical motion, and, since vertical motion and convergence tend to produce stability changes, a study of the applicability of the development equation to this heavy thundershower situation has seemed appropriate.

This has been done by attempting to analyze data for the Chicago flood situation in the various functional forms of the separate terms of the equation:

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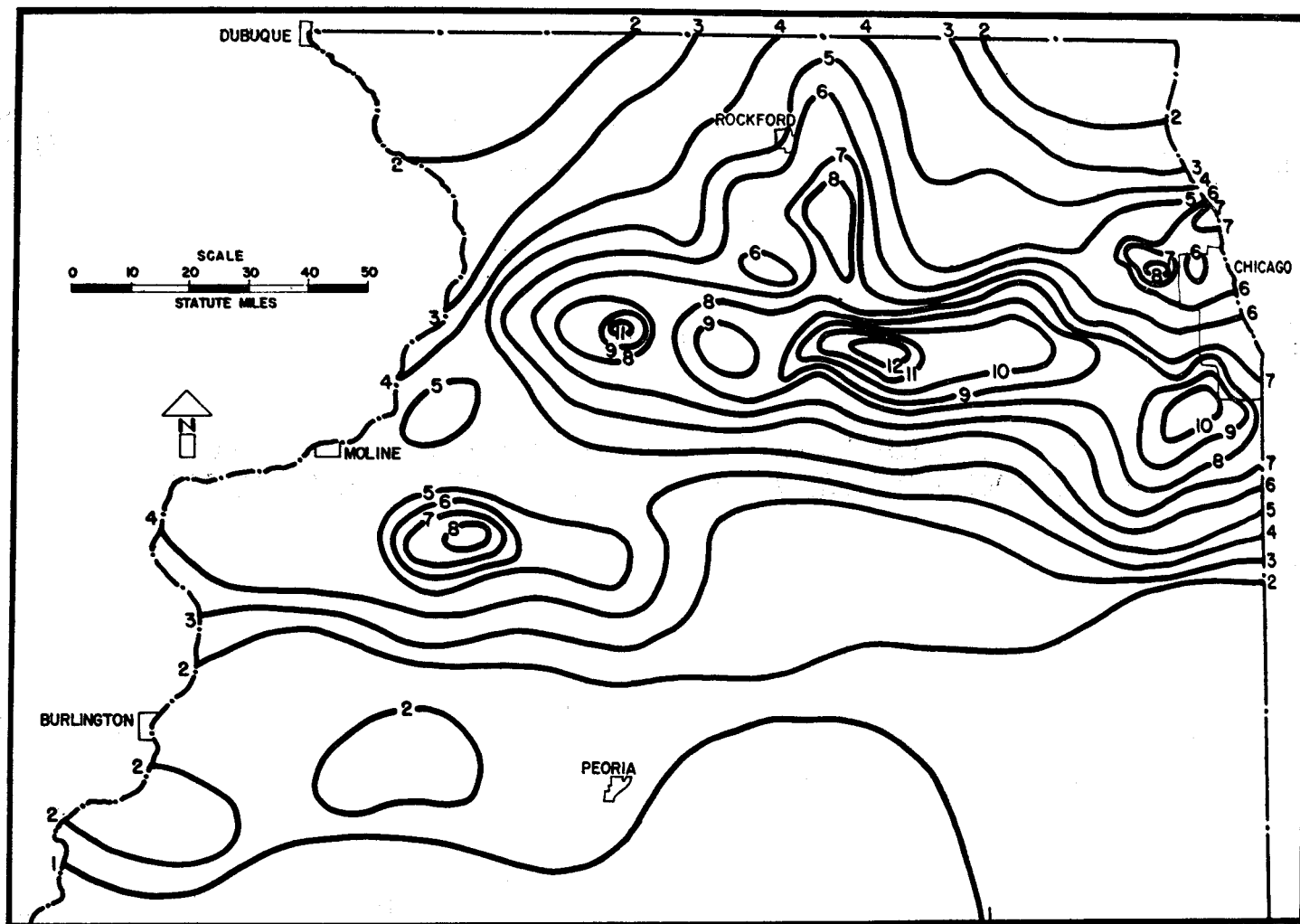


FIGURE 1.—Total storm rainfall (inches) October 9–10, 1954. From [2].

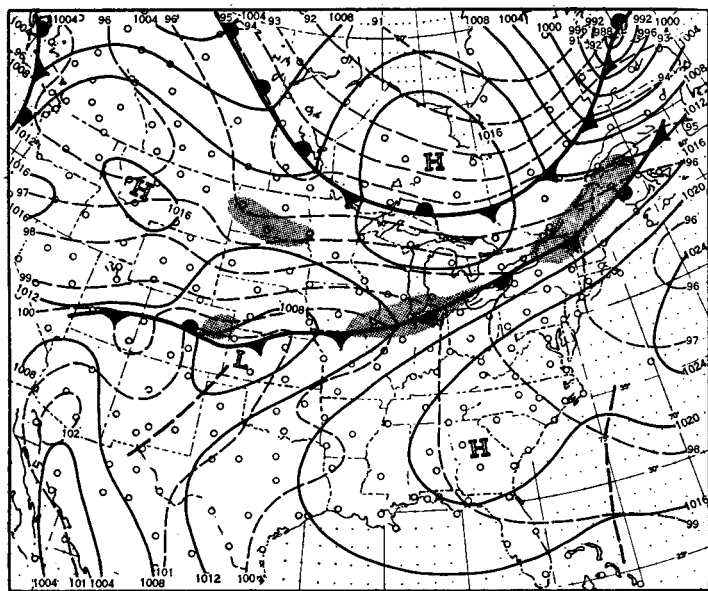


FIGURE 2.—Surface chart at 0330 GMT on October 10, 1954 and 1000–700-mb. thickness contours in hundreds of feet (dashed) at 0300 GMT on October 10, 1954. Shading shows active precipitation. (From [3]).

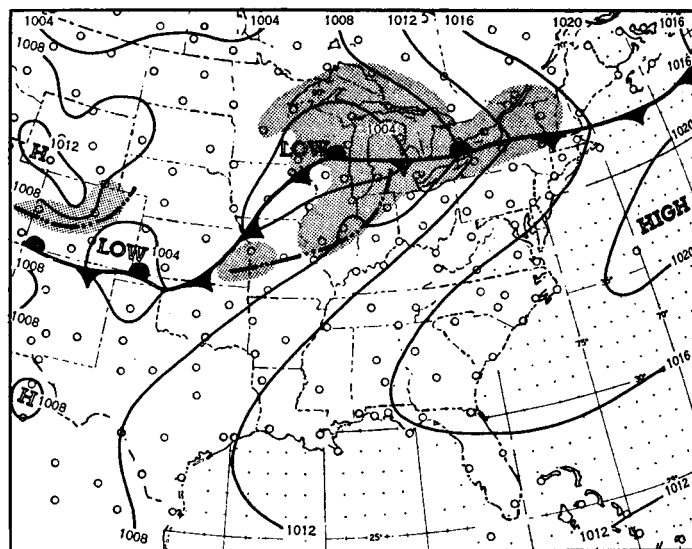


FIGURE 3.—Surface chart at 0330 GMT on October 11, 1954. (From [3]).

$$-Q_0 D_0 = A_{QL} + \mathbf{V}_0 \cdot \nabla Q_0 - \frac{g}{f} \nabla^2 A_h$$

$$- \frac{R}{f} \nabla^2 \left[\log \frac{p_0}{p} \left(\overline{\omega(\Gamma_a - \Gamma)} + \frac{1}{c_p} \frac{d\bar{W}}{dt} \right) \right]$$

$-Q_0 D_0$ represents the product of absolute vorticity and development (convergence) at sea level or 1000 mb.

A_{QL} represents $-(\mathbf{V} \cdot \nabla Q)_L$ or vorticity advection at the level of non-divergence.

A_h represents $-\mathbf{V} \cdot \nabla h$ or advection of an isobaric layer whose thickness is h .

p is the pressure at the level of non-divergence.

$\overline{\omega(\Gamma_a - \Gamma)}$: $\omega = \frac{dp}{dt}$ denotes vertical velocity where p is pressure and t is time.

$\Gamma_a = \frac{dT}{dp}$ = adiabatic lapse rate of temperature T with respect to pressure.

$\Gamma = \frac{\partial T}{\partial p}$ = actual lapse rate with respect to pressure.

The bar denotes the mean value from the level of non-divergence to 1000 mb.

$\frac{1}{c_p} \frac{d\bar{W}}{dt}$: c_p is specific heat at constant pressure.

$\frac{d\bar{W}}{dt}$ is the heat (other than latent) supplied to a unit mass per unit time.

R is the gas constant.

Subscript 0 denotes sea level (or 1000-mb.) value.

Vorticity advection patterns in the vicinity of, and upstream (southwest quadrant) from, northern Illinois at sea-level (A_{Q_0}) and in the middle (500 mb.) troposphere or near the tropopause (300 mb. or 200 mb.) (A_{QL}) did not reveal any large contribution to low-level convergence. From an examination of the charts for October 9, 1500 GMT, October 10, 0300 GMT and October 10, 1500 GMT, the largest value of A_{QL} was found to be 5.8×10^{-9} sec.⁻². This was computed from the 200-mb. chart for October 10, 1500 GMT.

No attempt was made in this limited study to locate the height of the level of non-divergence. It was assumed to be at 300 mb. or above, which experience (Petterssen, [4]) has shown to be frequently the case before intensification of any sea level system, and in this case no intensification of any sea level system of the scale of extratropical cyclones occurred.

However, analysis of patterns of the second term, the Laplacian of thermal advection, revealed larger contributions for the layer 1000–500 mb. as shown in figures 4 to 6 amounting to 30×10^{-9} sec.⁻² in the vicinity of or upstream (southwest quadrant) from northern Illinois. These data were computed separately using a 300-km. grid for layers 1000–700 mb. and 700–500 mb. and added algebraically. Neither the 500–300-mb. nor 500–200-mb.

layer was used in these computations because the thermal advection was relatively weak for those layers in this situation.

Two pronounced minima of the Laplacian of thermal advection are revealed in figures 4 and 6 as approaching northern Illinois on the 9th and 10th respectively. These two patterns suggested the occurrence of two specific areas of low-level convergence, while an intermediate pattern of opposite sign, figure 5, contributed to low-level divergence. The two patterns of low-level convergence appeared to be associated in time and space with: (1) the beginning of showers on the afternoon of the 9th (the first indication in the regular reporting network of Weather Bureau stations was a trace of rain at Bradford, Ill., on the 1830 GMT chart); and (2) the development of heavy showers which moved across the Chicago area on the afternoon of the 10th.

The stability, or rather potential instability ($\overline{\Gamma_a - \Gamma}$) was evaluated from a Showalter-type stability index [5], but using values from that level at or below 700 mb. having the *largest equivalent potential temperature* (usually the level of greatest moisture content), rather than 850-mb. values, unless of course that level had the largest equivalent potential temperature. The difference in the 500-mb. temperature of the ambient air and the temperature at 500 mb. of the lifted parcel (lifted from the level of maximum equivalent potential temperature) gives a measure of the difference between adiabatic lapse rate and actual lapse rate, $(\Gamma_a - \Gamma)$, for a given layer. The temperature and pressure for the parcel to be lifted and that for the ambient air are initially the same since they are taken initially at the same significant level. Values of this index of potential instability were plotted and analyzed. The fact that lapse rates were taken over slightly different height intervals (but most were from near 900 to 500 mb.) did not influence the values of the index as much as would the selection of one arbitrary level as being most representative for maximum lifted parcel temperature values at 500 mb.

It is notable in this case that successive soundings showed that lapse rates consistent with conditional instability were maintained despite the usual tendency for lapse rates to approach the pseudo-adiabatic in cases of heavy rain. In this case the potentially unstable air continued to flow into the more localized convergence area and the heavy precipitation was not sufficiently widespread to modify the lapse rates of this potentially unstable air upstream.

The stability-vertical motion term from the development equation,

$$- \frac{R}{f} \nabla^2 \log \frac{p_0}{p} \overline{\omega(\Gamma_a - \Gamma)}$$

cannot be quantitatively evaluated since no measurements of vertical motion are available for this situation. However, the area of upward motion can be qualitatively outlined making use of indirect aerology through the

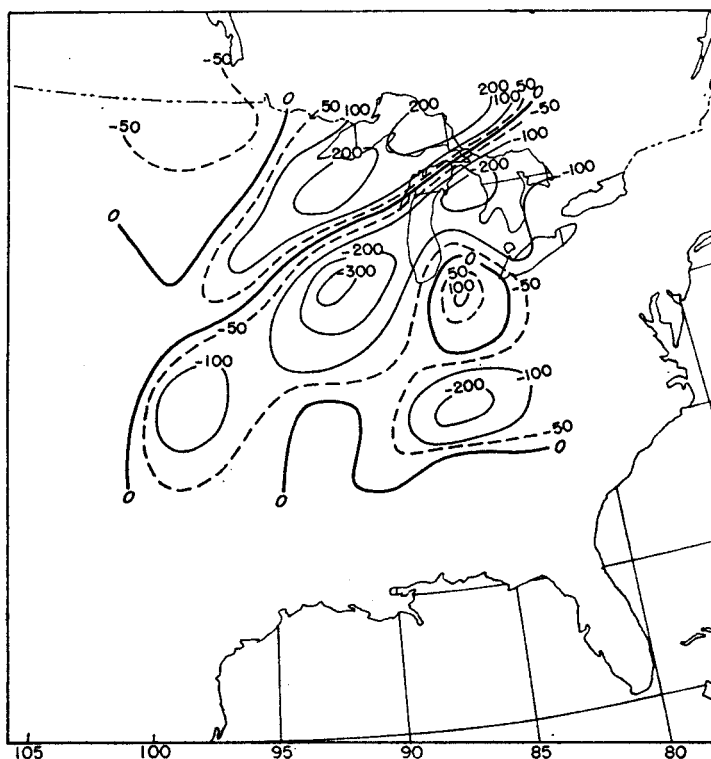


FIGURE 4.—Laplacian of thermal advection for 1000–500-mb. layer, October 9, 1954, 1500 GMT (units $\times 10^{-10} \text{ sec.}^{-2}$).

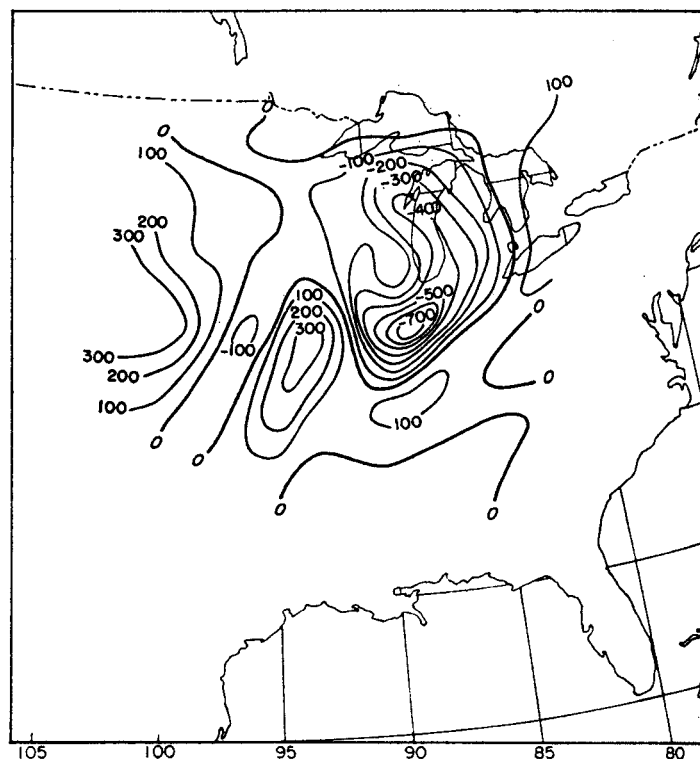


FIGURE 6.—Laplacian of thermal advection for 1000–500-mb. layer, October 10, 1954, 1500 GMT.

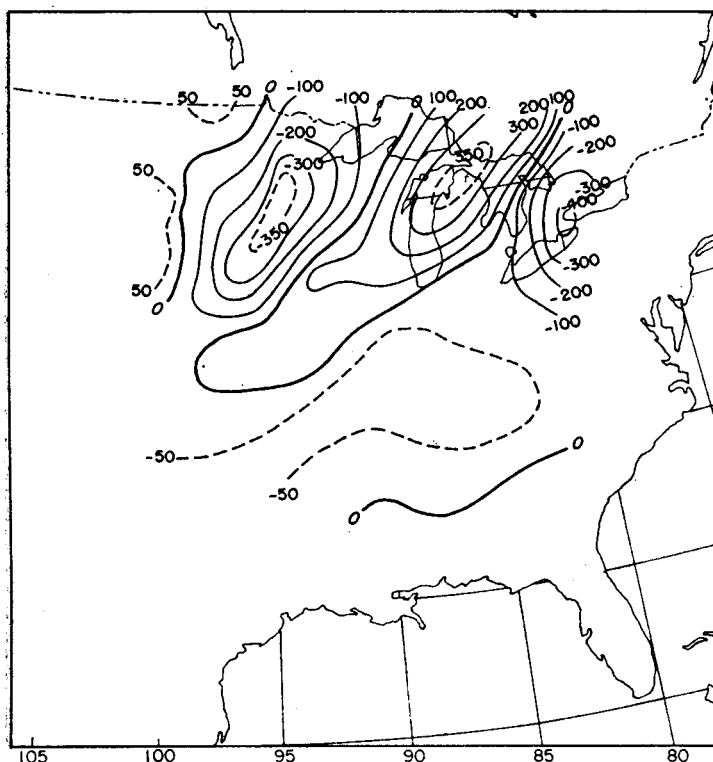


FIGURE 5.—Laplacian of thermal advection for 1000–500-mb. layer, October 10, 1954, 0300 GMT.

examination of cloud data. Overcast areas are cross-hatched on the patterns of the stability factor in figures 7–11. Reference to these figures then gives a qualitative indication of the contribution of the Laplacian of this term. These areas of potential instability over or just upstream from Chicago are consistent with the development and movement of low-level convergence and precipitation over the Chicago area on the afternoons of the 9th and 10th, and with the continuance of some precipitation into the early morning hours of the 10th.

A discussion of the 12-hour continuity of these patterns before and during the period of heavy rain follows:

At 1500 GMT on the 8th (fig. 7) more than 24 hours before the rains began, considerable cloudiness was associated with a trough northwest of Chicago, and some light rains occurred, mostly to the north of Chicago. However, analyses of the lapse rates showed that important potential instability was not yet indicated by the index of lapse rate difference which gave a plus 1 value at Omaha and Topeka. (Larger negative values of the index indicate greater instability).

By 0300 GMT on the 9th (fig. 8) a marked change in the potential instability factor values had occurred but the area of overcast skies remained north and east of Chicago suggesting that little vertical motion had developed upward from the lowest moist layer by this time, especially to the south and west of Chicago.

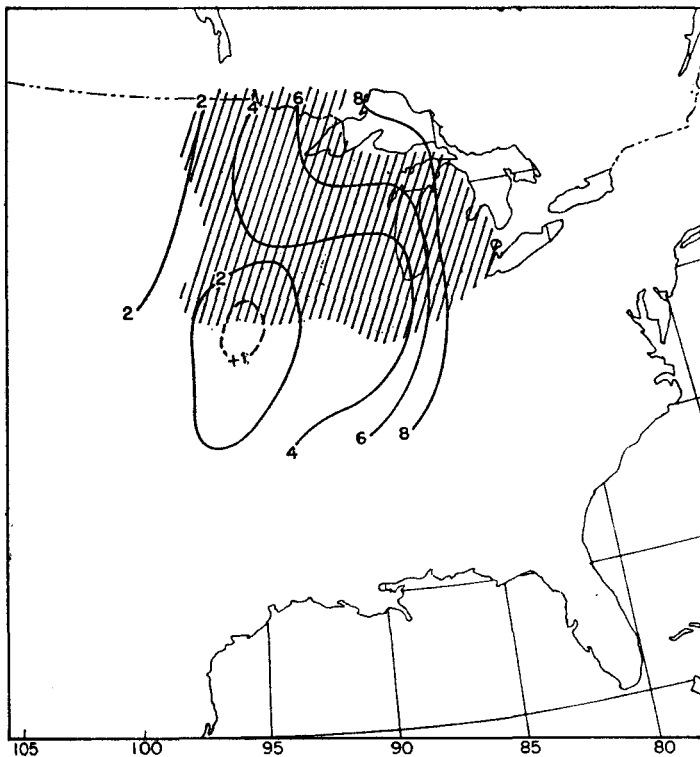


FIGURE 7.—Stability index, October 8, 1954, 1500 GMT. Cross-hatched area represents mostly overcast skies.

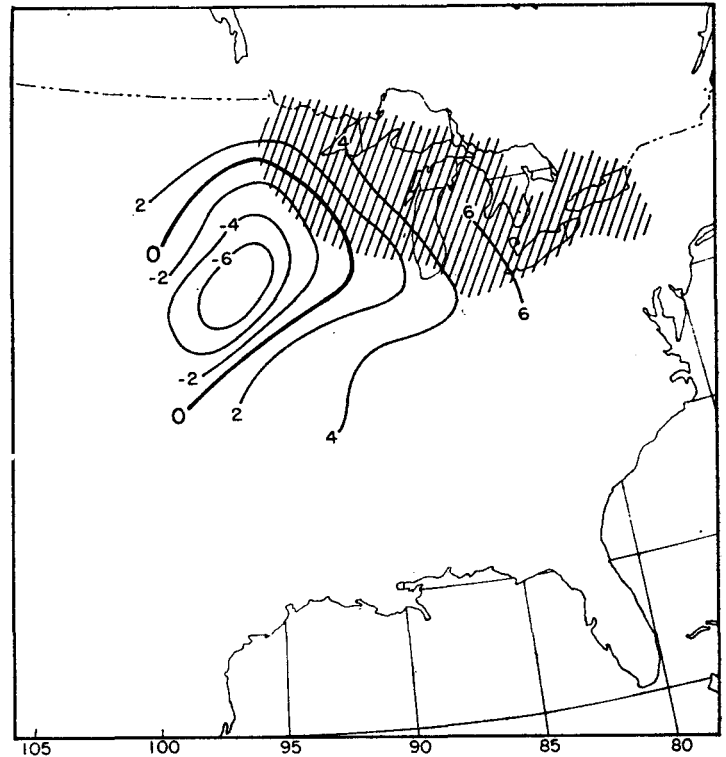


FIGURE 8.—Stability index, October 9, 1954, 0300 GMT. Cross-hatched area represents mostly overcast skies.

Not until the 1500 GMT chart of the 9th (fig. 9) was there a good indication of cloudiness developing upstream from Chicago within the area of potential instability and even then a Laplacian computation using a small grid (assuming uniform upward motion over the entire cloudy area) would have given little immediate indication of any important contribution by the vertical motion-stability term to low-level vertical motion or convergence. This was due to rather straight isolines of the instability factor and also little shear in the pattern. However, it is recognized that such detail in the analysis is not very reliable due to wide spacing of the points for which data were available.

The chart of the 10th at 0300 GMT (fig. 10) showed a much larger curvature to the isolines of stability index from northwestern Illinois eastward to southeastern Lower Michigan. This pattern was within the area where considerable cloudiness was observed and upward motion was presumed to be present. With upward motion and sharp curvature of the stability index pattern in the proper sense, the Laplacian of vertical motion-stability term could make an appreciable contribution toward low-level convergence.

A computation from the center of the area of potential instability included within the cloudy area, using an assumed upward wind speed (uniform over the entire area) of 10^{-2} mb. sec. $^{-1}$ showed a value of 12×10^{-9} sec. $^{-2}$ as a

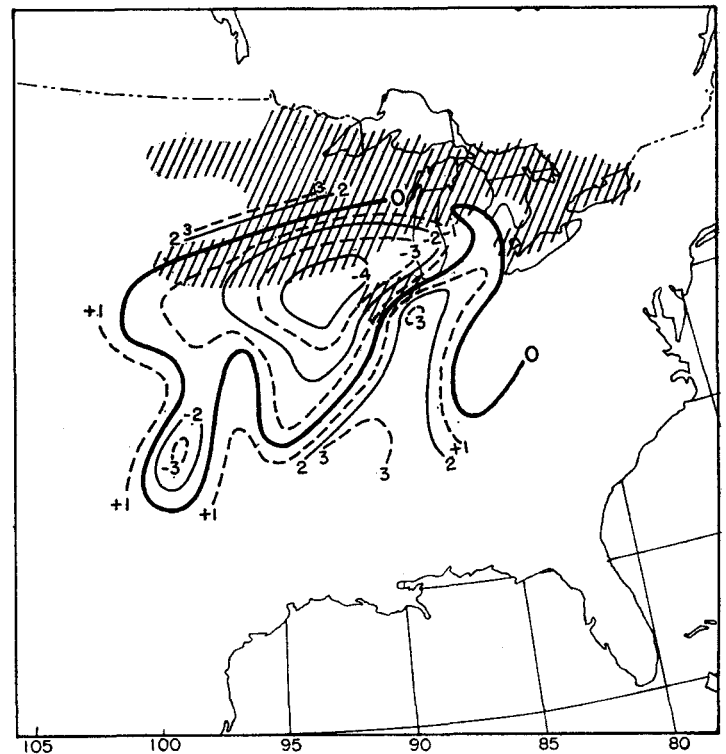


FIGURE 9.—Stability index, October 9, 1954, 1500 GMT. Cross-hatched area represents mostly overcast skies.

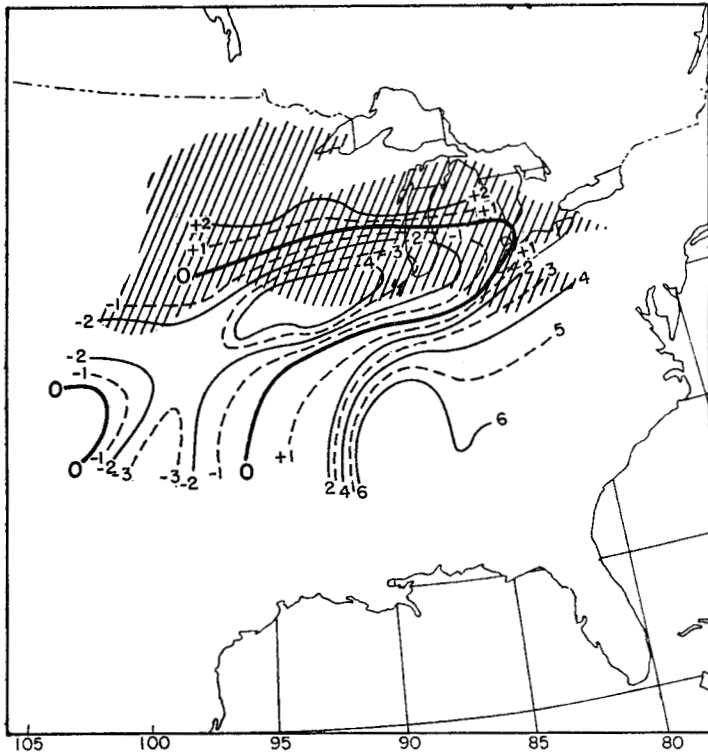


FIGURE 10.—Stability index, October 10, 1954, 0300 GMT. Cross-hatched area represents mostly overcast skies.

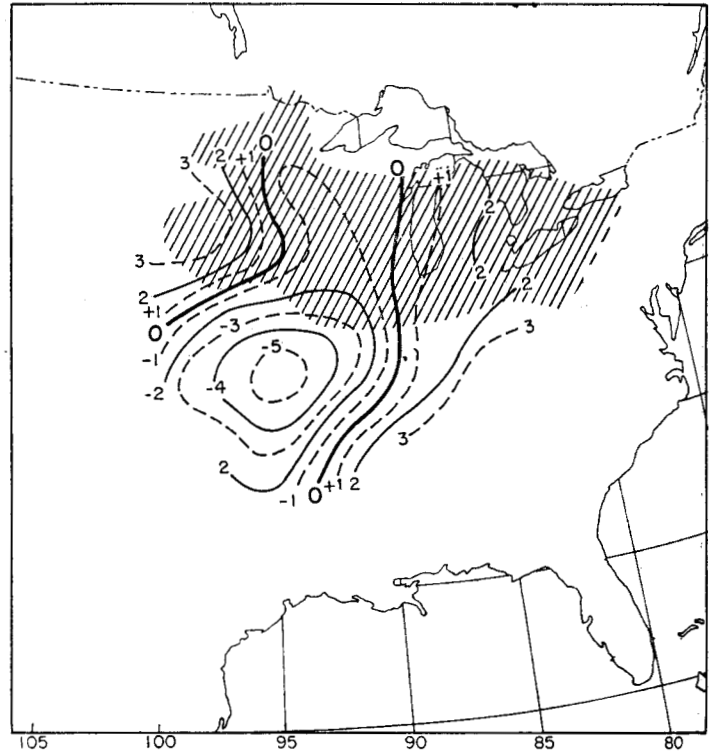


FIGURE 11.—Stability index, October 10, 1954, 1500 GMT. Cross-hatched area represents mostly overcast skies.

representative contribution of this term, which is greater than the vorticity advection computation but less than the Laplacian of thermal advection values in this series.

If upward motions were greater where the potential instability was also greater, as seems likely, the Laplacian of the product of vertical motion and instability in this term could have been somewhat larger.

Data from certain rainfall studies and from a recent study by Smagorinsky [6] suggest that the average horizontal gradients of vertical velocity in the vicinity of an area of heavy rainfall (say 5 inches and more in 24 hours) may easily amount to 20 to 80 cm. sec.⁻¹ over the grid distance of 300 km. When such gradients of vertical motion with a central maximum are superimposed upon a maximum of potential instability, then the individual instability factors multiplied by the individual vertical velocities leads to Laplacian values which are half an order of magnitude greater than the original computation of 12×10^{-9} sec.⁻² which was obtained using a uniform upward field of motion of about 10^{-2} mb. sec.⁻¹.

This additional magnitude would make the buoyancy term equal to or greater than the Laplacian of thermal advection.

The buoyancy term then becomes an increasingly important consideration in cases of this type as vertical velocities increase over more or less local areas giving a chain reaction or "bootstrap effect" contribution to low-level convergence.

Again on the 10th at 1500 GMT (fig. 11) a significant contribution was indicated by the Laplacian of the instability (assuming upward motion) with the cloudy area upstream (southwest quadrant) from northern Illinois.

No practicable means was available for evaluating the non-adiabatic term in the development equation.

The heavy rains indicated that low-level convergence was present and quite strong. But little surface development as evidenced by increasing cyclonic circulation and deepening of central pressures, occurred in this situation.

In an attempt at explanation one might conjecture that low-level vorticities (Q_0) apparently were localized into small patterns the size of groups of thunderstorm cells and in the absence of any strong large-scale vorticity advection aloft tended to dissipate perhaps due to friction and turbulent transport of momentum and vorticity near the ground and also possibly due to thermal modifications with cooling in the areas of heavy rain. The recurring strong thunderstorm activity and associated convection to high levels suggests that the level of non-divergence did not drop and that compensation occurred mainly between the stratosphere and troposphere rather than within the troposphere. The lack of surface circulation intensification on an extratropical scale may also be consistent with the lack of any marked vorticity advection at high levels, which according to the working hypothesis concerning development (Petterssen, Dunn, and Means [7]) is usually present with surface development.

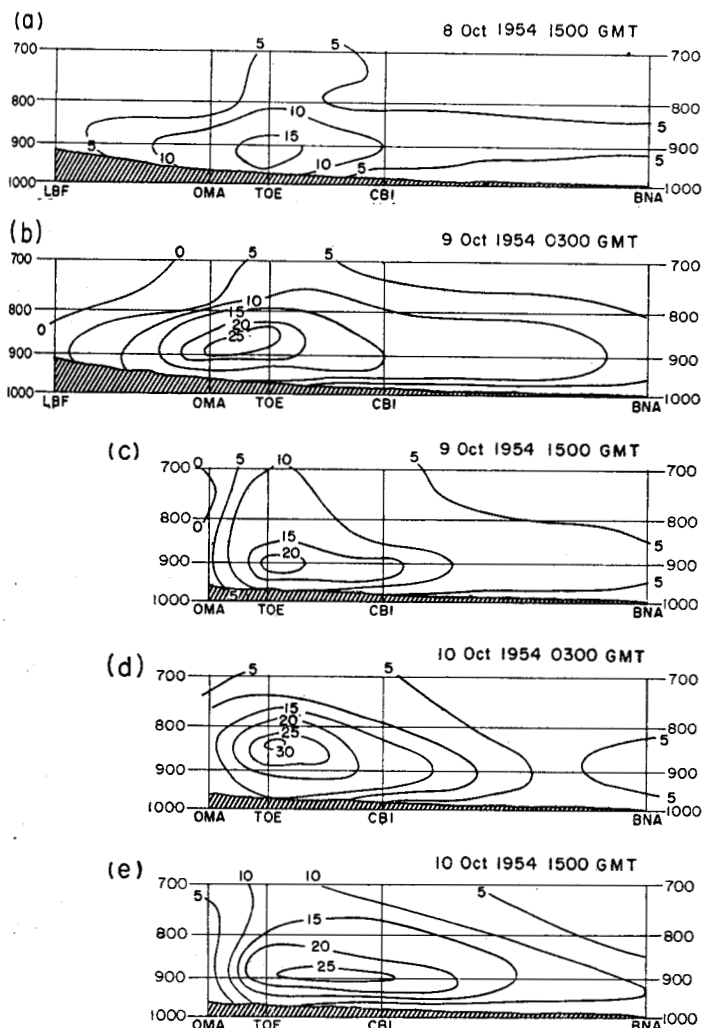


FIGURE 12.—Moisture transport normal to cross-section, October 8-10, 1954. Units in gr. sec.^{-1} for a unit cross-section 1 mb. high by 1 cm. wide.

The data suggest that the Laplacian of thermal advection contributed significantly initially to the low-level vertical motion and convergence in these heavy rains, and that after the development of cloudiness and convective activity, the Laplacian of the vertical motion-stability term also may have contributed quite significantly to the maintenance of low-level convergence.

3. FORECASTING SIGNIFICANCE

The question arises from the forecasters' point of view as to the possibility of identifying the mechanism that was responsible for developing and increasing potential instability. Charts for two periods (October 8, 1500 GMT and October 9, 0300 GMT) are given in figures 7 and 8. The potential instability was not only present but strong with a minus 6 central value on the 9th at 0300 GMT as contrasted with a plus 1 central value at 1500 GMT, October 8, giving a net drop of 7°C. in the index of potential instability for the Omaha soundings over this

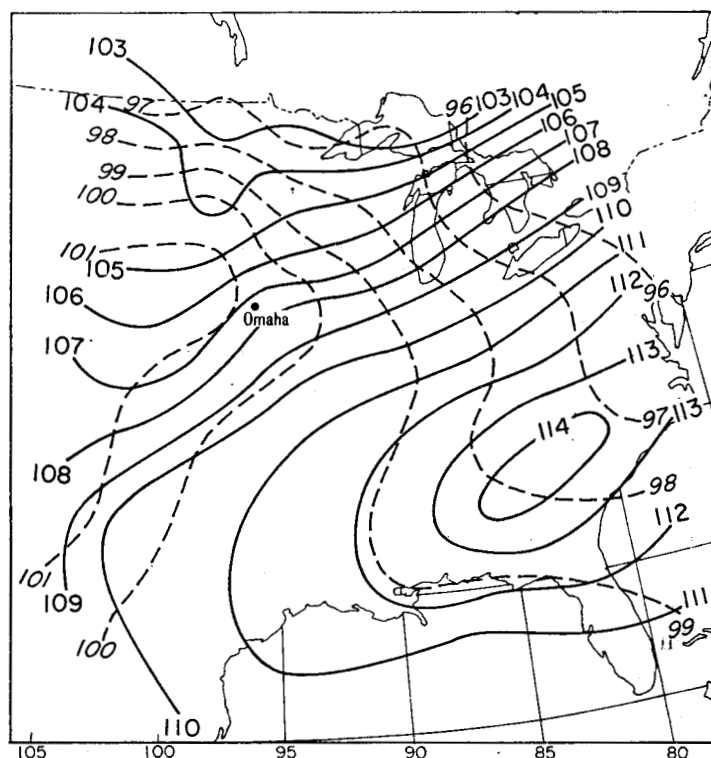


FIGURE 13.—Thickness and mean flow, 1000-700 mb. October 9, 1954, 0300 GMT. Dashed lines are thickness labeled in 100's of feet. Solid lines are mean flow labeled as sum of 1000- and 700-mb. heights in 100's of feet.

12-hour period. The marked change was associated with an influx of warm moist air below 800 mb. and especially near the 900-mb. level. This influx of warm moist air was associated with the development of the low-level jet (fig. 12 a and b). The 1000-700-mb. mean contour and thickness patterns upstream from Omaha (fig. 13) show the typical contour-isotherm relationship (Means [8]) with warmer air toward lower contour values, which is hydrostatically consistent with the occurrence of the low-level jet. The corresponding 850-mb. chart shows similar patterns.

The primary forecast difficulty in this case was due to the failure of appreciable cloudiness to develop upstream from Chicago until almost the very beginning of the period of heavy thundershowers, also the lack of any well-defined impulse as identified by a katalobar-analobar couplet which forecasters usually associate with moving or developing weather situations.

The potential instability was maintained throughout the period of heavy rains by continued transport of warm moist air in the low-level jet. This is depicted in figure 12 for each of the 12-hour periods from the 8th at 1500 GMT through the 10th at 1500 GMT. The low-level moisture transport increased markedly during the period October 8, 1500 GMT to October 9, 0300 GMT and remained strong while the jet core moved very little laterally, remaining in the area between Columbia, Mo. and Omaha, Nebr.

Greatest transport was between 900 and 850 mb. and averaged 3 times as great in value in the core as at 700 mb. just above the jet core.

4. CONCLUSIONS

In summary then, the forecaster might attempt to forecast the development of a strong but localized area of warm advection especially in the lower troposphere (below the level of non-divergence), the development of a local minimum of negative stability index values, and an abundant supply of moisture. All of these were associated in this case with a low-level jet which in turn was associated with the formation and extension of a low-level warm tongue.

The chain reaction contribution of locally increasing vertical velocities to the importance of the buoyancy term is suggested.

This case also suggests the value of a maximum equivalent potential temperature point in the lower portion (below 700 mb.) of the sounding for a Showalter stability index since values of equivalent potential temperature taken at 850 mb. are not always representative of high values that are found below 700 mb., especially near the 900-mb. level.

The maximum moisture transport was found more frequently in the vicinity of the 900-mb. level than at 850 mb.

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